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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Life cycle assessment of silicon wafer processing for microelectronic chips and solar cells

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Abstract
Purpose The life cycle assessment of silicon wafer processing for microelectronic chips and solar cells aims to provide current and comprehensive data. In view of the very fast market developments, for solar cell fabrication the influence of technology and capacity variations on the overall environmental impact was also investigated and the data were compared with the widely used ecoinvent data.
Methods Existing material flow models for silicon wafer processing for microelectronic chips and solar cells used for engineering and planning formed a starting point for this analysis. The models represent an average of widely used processes and associated process equipment. The resulting input/output tables formed the data basis for the life cycle assessment. This is a cradle-to-gate investigation, consisting of primary gate-to-gate data for wafer processing. The upstream processes of the necessary inputs were supplemented with data from ecoinvent v2.0. Subsequent manufacturing steps, utilization, and waste disposal of the final products were not included. The software used for creating the inventory and impact assessment was Umberto version 5.5. The Impact 2002+ method was applied for impact assessment.
Results For both semiconductor and solar cell fabrication, energy consumption and upstream chemicals production are most relevant for the overall potential environmental impact when only the gate-to-gate processes are considered. The upstream process for wafer production is dominant in solar cell fabrication, but exerts little influence on semiconductor fabrication. In the case of semiconductor fabrication, a comparison with the present ecoinvent dataset "wafer, fabricated, for integrated circuit, at plant" shows large differences.
Conclusions In the case of silicon solar cells, the results of this study and the ecoinvent data are very similar and the impact of different fabrication processes appears to be minor.

Keywords Crystalline silicon · DRAM · Ecoinvent · Fabrication · Impact 2002+ · Life cycle assessment · Logic chip · Memory chip · Microelectronic · Photovoltaic · Semiconductor · Solar cell · Wafer

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1 Introduction

The semiconductor and solar industries are fast developing branches with increasing efficiency rates. Therefore life cycle data too are subject to change.

There is little literature on life cycle assessments of semiconductor fabrication, even though this is a key technology. One of the first and often cited studies was carried out by (Williams et al. 2002) who used an average set of material inputs from an anonymous industry source.

Table 1 Differences and similarities between wafer processing for silicon solar cells and microchips

	Solar cell production	Microchip production
General properties of the productions		
Raw wafer	Silicon, rectangular, 156×156 mm	Silicon, round, 300 mm diameter
Silicon wafer purity	Solar grade (lower than electronic grade)	Electronic grade
No. of process steps	5 to 7	Typically 400
Patterned layers	1	Typically 20+
Process sequence	Linear	Cycles
Typical cycle time	5 h	25 days
General types of processes		
Wet etching, HF, HNO_3, other inorganic acids	Applied	Applied
Atmospheric deposition from the gas phase	Applied for dopant and passivation layers	Applied for dopant, barrier, and semiconductor layers
Vacuum deposition from the gas phase	Applied for passivation layers	Applied for dopant, barrier, semiconductor and metal layers
Sputtering for metallization	Not used	Applied
Dry etching from the gas phase	Phased out	Applied
Process sequences for typical purposes		
Patterning by photolithography	Not used	Applied as a key process, structures smaller than 0.1 µm
		Implies a sequence of resin covering, photo exposure, developing the resin pattern, etching, and removing of resist.
Patterning by printing	Regularly used, structures of 100 µm	Not used implies a two step procedure with printing and drying/sintering
Doping by deposition and diffusion	Applied	Applied
Doping by ion implant	Not used	Applied as a key process
Planarization by grinding or deposition techniques	Not used	Applied as a key process

Murphy and colleagues assessed the production line by developing parametric inventories for wafer fabrication processes. Their data were ascertained by measuring in an academic facility (Murphy et al. 2003). Krishnan and colleagues also included the infrastructure processes and worked out a hybrid life cycle inventory of semiconductor manufacturing (Krishnan et al. 2008). Boyd and colleagues assessed logic chips over a 15-year period. Their study is composed of production LCA data, based on emissions measurements, process formulas and equipment electrical tests (Boyd et al. 2009, 2010). Krishnan and Boyd, both report data from bottom-up inventory from Applied Materials which is a producer of the equipment and facility systems used in semiconductor fabrication. Liu and colleagues conducted a gate-to-gate life cycle assessment study for DRAM production in Taiwan (Liu et al. 2010).

More comprehensive data exist for solar cells, such as that collected by the European Crystal Clear project (de

Table 2 Factors for conversion of time-related material and energy flows to the reference flows

	DRAM	Logic		DRAM	Logic	
Capacity (input gross)	4,900	1,700	wf/week	346	120	m^2/week
Capacity (input gross)	29.2	10.1	wf/h	2.06	0.715	m^2/h
Test wafer	0.92	1.03	wf/h	0.065	0.073	m^2/h
Throughput (input net)	28.3	9.09	wf/h	2.00	0.642	m^2/h
Loss (breakage and layer errors)	6	6	%	6	6	%
Throughput (output)	26.6	8.54	wf/h	1.88	0.604	m^2/h
Process yield	91	84	%	91	84	%
Wafer diameter, 0.300 m						
Wafer area, 0.071 m^2/wf						
Hours per week, 168 h/week						

Table 3 Primary data for the demand of process chemicals, gases, and water

Chemical, gas, or water		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
2-Methylaminoethanol	kg	3.29E+00	1.75E+00	5.45E+00
Acetone	kg	8.37E−01	4.46E−01	1.39E+00
Argon	kg	2.50E+01	1.33E+01	4.14E+01
AsH_3	kg	2.43E−03	1.30E−03	4.03E−03
AsH_3 0.7% in H_2	kg	5.71E−05	3.04E−05	9.45E−05
B_2H_6 5% in N_2	kg	2.05E−03	1.09E−03	3.40E−03
BCl_3	kg	1.45E−02	7.74E−03	2.40E−02
80% H_20, 20% ammonium fluoride/HF (20:1)	kg	6.20E+00	3.30E+00	1.03E+01
80% H_20, 20% ammonium fluoride/HF (500:1)	kg	2.79E+00	1.49E+00	4.62E+00
Butyl acetate	kg	1.78E+00	9.47E−01	2.94E+00
C (undef.)	kg	2.55E−01	1.36E−01	4.22E−01
C_2F_6	kg	3.63E−01	1.93E−01	6.01E−01
C_4F_8	kg	3.47E−02	1.85E−02	5.74E−02
C_5F_8	kg	3.18E−02	1.69E−02	5.27E−02
CF_4	kg	1.62E−01	8.63E−02	2.68E−01
CH_2F_2	kg	1.16E−02	6.17E−03	1.92E−02
CH_3F	kg	2.02E−03	1.08E−03	3.35E−03
CHF_3	kg	4.17E−03	2.22E−03	6.90E−03
Cl_2	kg	2.48E−02	1.32E−02	4.11E−02
CO	kg	2.22E−03	1.19E−03	3.68E−03
Cu(hexafluoro-acetylacetonate)$_2$	kg	5.32E−02	2.84E−02	8.81E−02
$CuSO_4$	kg	3.46E+01	1.84E+01	5.73E+01
1% HF in H_2O	kg	2.40E+01	1.28E+01	3.97E+01
EDTA	kg	1.74E+00	9.27E−01	2.88E+00
Ethyl lactate	kg	1.50E+01	8.02E+00	2.49E+01
1% F_2 in Kr	kg	7.38E−04	3.93E−04	1.22E−03
Gamma-butyrolactone	kg	7.11E−02	3.79E−02	1.18E−01
H_2	kg	1.20E+00	6.38E−01	1.98E+00
H_2O_2	kg	2.20E−01	1.17E−01	3.64E−01
H_2O_2 (30%)	kg	3.17E+01	1.69E+01	5.26E+01
H_2SO_4	kg	1.77E+01	9.42E+00	2.93E+01
H_2SO_4 (98%)	kg	2.62E+01	1.40E+01	4.34E+01
H_3PO_4 (85%)	kg	4.13E+00	2.20E+00	6.84E+00
HBr	kg	3.13E−02	1.66E−02	5.17E−02
HCl	kg	1.31E−01	6.96E−02	2.16E−01
HCl (37%)	kg	7.39E+01	3.94E+01	1.22E+02
He	kg	3.34E−04	1.78E−04	5.53E−04
HF	kg	1.86E−01	9.89E−02	3.07E−01
HF (50%)	kg	2.01E+01	1.07E+01	3.33E+01
HF liq (0.5%)	kg	1.20E+00	6.39E−01	1.99E+00
Hexamethyldisilazane	kg	1.37E−01	7.32E−02	2.28E−01
HNO_3	kg	5.60E−01	2.98E−01	9.27E−01
HNO_3 (69%)	kg	2.48E+00	1.32E+00	4.11E+00
HNO_3/HF 50%	kg	1.55E+00	8.26E−01	2.57E+00
Isopropanol	kg	1.86E+01	9.88E+00	3.07E+01
KOH	kg	6.98E+01	3.72E+01	1.16E+02
KOH (40%)	kg	2.58E−01	1.38E−01	4.28E−01
Kr/Ne	kg	3.67E−04	1.96E−04	6.08E−04

Table 3 (continued)

Chemical, gas, or water		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
Methyl nonafluorobutyl ether	kg	6.34E−01	3.38E−01	1.05E+00
N_2	kg	1.23E+03	6.56E+02	2.04E+03
N_2O	kg	2.21E−01	1.18E−01	3.65E−01
NaOH	kg	4.29E−01	2.28E−01	7.10E−01
NF_3	kg	9.70E−02	5.17E−02	1.61E−01
NH_3	kg	3.05E−02	1.63E−02	5.06E−02
NH_3 (25%)	kg	3.91E+00	2.08E+00	6.47E+00
NH_4OH	kg	5.71E−02	3.04E−02	9.46E−02
NH_4OH (2%)	kg	1.80E+00	9.59E−01	2.98E+00
N-methyl-2-pyrrolidone	kg	3.30E+00	1.76E+00	5.47E+00
O_2	kg	1.34E+02	7.14E+01	2.22E+02
Propylene glycol methyl ether acetate (PGMEA)	kg	1.76E+00	9.40E−01	2.92E+00
PH_3	kg	2.13E−03	1.14E−03	3.53E−03
PH_3 1% in H_2	kg	4.41E−05	2.35E−05	7.31E−05
PH_3 30% in SiH_4	kg	3.14E−03	1.67E−03	5.19E−03
Triethyl phosphate ($PO(OC_2H_5)_3$)	kg	2.67E−02	1.42E−02	4.42E−02
Trimethyl phosphate ($PO(OCH_3)_3$)	kg	6.90E−03	3.67E−03	1.14E−02
Propylene glycol	kg	4.32E−01	2.30E−01	7.16E−01
Pure N_2	kg	1.99E+03	1.06E+03	3.30E+03
SF_6	kg	4.38E−01	2.33E−01	7.25E−01
$Si(OC_2H_5)_4$	kg	9.15E−02	4.88E−02	1.52E−01
Si_2H_6	kg	3.02E−04	1.61E−04	5.00E−04
$SiCl_4$	kg	5.23E−04	2.78E−04	8.65E−04
SiF_4	kg	1.00E−03	5.33E−04	1.66E−03
SiH_2Cl_2	kg	3.19E−02	1.70E−02	5.29E−02
SiH_4	kg	4.40E−02	2.35E−02	7.29E−02
Tetramethylammonium hydroxide	kg	1.70E+01	9.07E+00	2.82E+01
Trimethylvinylsilane	kg	3.22E−02	1.71E−02	5.33E−02
UHP-Ar	kg	2.25E+00	1.20E+00	3.72E+00
UHP-H_2	kg	2.44E−01	1.30E−01	4.05E−01
UHP-He	kg	1.36E−01	7.26E−02	2.26E−01
UHP-N_2	kg	1.35E+01	7.22E+00	2.24E+01
UHP-O_2	kg	3.67E+00	1.96E+00	6.08E+00
WF_6	kg	2.08E−01	1.11E−01	3.45E−01
Slurry overall	kg	5.71E+01	3.04E+01	9.45E+01
Thereof water	kg	5.13E+01	2.73E+01	8.50E+01
Thereof sodium hydroxide	kg	2.05E−02	1.09E−02	3.40E−02
Thereof silica sand	kg	5.71E+00	3.04E+00	9.45E+00
City water	kg	9.65E+04	5.14E+04	1.60E+05

Wild-Scholten 2007). Other literature sources are Jungbluth et al. (2005) or Stoppato (2008).

In the case of solar cell fabrication, given the very fast development of the market, the purpose of conducting a life cycle assessment was to investigate the influence of technology and capacity variations on the overall environmental impact. Especially for semiconductor fabrication, this analysis contributes to average, current and comprehensive life cycle data. The data obtained were compared with the widely used ecoinvent data.

In a recent research project, M+W Germany (Stuttgart, Germany, formerly M+W Zander FE GmbH) together with Pforzheim University carried out a life cycle assessment of crystalline silicon wafer processing for microelectronic chips and also for solar cells. Primary gate-to-gate data for these processes were provided by M+W Germany. The business

activities of M+W Germany include the engineering and construction of semiconductor and solar cell production facilities. Most of the world's producers in the electronics and solar cell industry are customers of the M+W Group.

Processing crystalline silicon and using the semiconducting effect form the basis of both industries. Processes of semiconductor fabrication are also found in solar cell fabrication, although processing microelectronic wafers is more precise. In crystalline silicon solar cell production typically five to seven process steps are applied in a linear sequence to the bare wafer, before the processed wafer is cut and used to build-up photovoltaic modules. Whereas in microchip fabrication there are up to 400 process steps before the array of microchips on the silicon wafer is finished and can be cut, packaged, and bound to electrical connections. These 400 process steps are run in about 12 specialized process areas, which require the wafer to circulate in the area of production. The different structure of production results also in very different times required to complete production ("cycle time").

2 Methodology

This is a cradle-to-gate investigation, consisting of primary gate-to-gate data for wafer processing for microelectronic chips and solar cells, respectively. The upstream processes of the necessary inputs were supplemented with data from ecoinvent v2.0 (ecoinvent Centre 2007).

Existing material flow models for semiconductor and solar cell fabrication used for engineering and planning represented a starting point of this analysis. The datasets were created using a multiple step approach, combining planning data with measurements of consumptions and emissions.

Because of the higher simplicity, PV production has been inspected building up several typical production scenarios using traditional and modern types of production processes and effluent treatment as well. These processes were integrated into a bottom-up model taking into account energy, water, gas, and chemical consumptions as input and emissions, wastewater, and waste as output.

The more complex semiconductor fabrication requires more aggregation of data:

Major input materials and energy consumption can be derived with good accuracy from measurements and purchasing data at semiconductor fab level, as well as output materials like emissions of major compounds into water and air, and the solid waste. This data availability for a set of installations with different size, productivity, and product type allows multi-parameter interpolation to derive data for a hypothetical "standard" fab as well. Its size and consumption/emission pattern is given below. The cited interpolation can be based also on design factors to support plausibility checks. Furthermore, the compilation of data has been backed by full energy and material flow modeling built up from modules of process families, effluent treatments, and combinations thereof. This model has been developed within the M+W Group since 1997 and validated module per module in the course of the years. Since the basic calculation model is available, any type of production can be analyzed. Provision of data which can be regarded as typical in a high number of cases and characterization of the major influence of parameters to the final impact in that typical case was the purpose for this analysis. One "standard" size and set of processes related to a 300-mm-wafer technology has been defined. Therefore, the resulting input/output tables do not represent a specific production facility but they contain average data for approximately 80% of the world's semiconductor fabrication.

The software used for creating the inventory and impact assessment was Umberto® version 5.5. The Impact 2002+ method (Jolliet et al. 2003) as implemented in ecoinvent v2.0 was applied for the impact assessment. In addition to new concepts for human toxicity and ecotoxicity, this method involves existing characterization methods such as Eco-indicator 99 and CML 2001. The impact assessment results in 14 midpoint impact categories. Eleven of these are aggregated using different damage models to form the damage categories human health, ecosystem quality, and resources. As no reliable damage models to relate quantitatively to human health and ecosystem quality exist for climate change so far, the impact category climate change is shown separately (Table 1).

Table 4 Primary data for the demand for electric power and natural gas

Energy		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
Electric power (production)	kWh	1.17E+04	6.25E+03	1.94E+04
Electric power (facilities)	kWh	4.71E+03	2.51E+03	7.80E+03
Electric power (mech. cooler)	kWh	1.76E+03	9.37E+02	2.91E+03
Electric power (others)	kWh	5.54E+01	2.95E+01	9.18E+01
Natural gas	kg	2.75E+01	1.47E+01	4.55E+01

Table 5 Estimation of transport distances

Transport		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
Transport, lorry >16 t, fleet average	tkm	215	1.15E+02	3.71E+02
Transport, freight, rail	tkm	580	3.09E+02	9.60E+02

3 Semiconductor fabrication

3.1 Scope

Silicon semiconductor fabrication is an essential technology in microelectronics, as silicon semiconductors form the basis for integrated circuits. The fabrication of integrated circuits can be subdivided into three phases (Hilleringmann 2004):

- Production of crystalline silicon disks (wafer)
- Integration of electric functions in planar process (wafer processing)
- Packaging of integrated circuits

This study investigates the second phase, distinguishing between wafer fabrication for memory and for logic devices. Unlike memory devices, which are structured relatively simply, logic devices are used to produce microchips with a more complex structure, such as microprocessors for example. A microchip contains only a small part of the wafer, called the die. The wafer is diced into hundreds of dies after being finished. For example a wafer that is 300 mm in diameter can be diced into 491 Pentium 4 processors (Krishnan et al. 2008).

The data underlying this study refer to an average fabrication process of DRAM memory devices on wafers with a diameter of 300 mm (12 in.), which is the current state of the art. The production of logic wafers can be derived by adjusting capacity and yield. The equipment and processes are in principle the same, but the logic wafer must go through these processes more frequently. DRAM wafer fabrication needs approximately 250 and logic wafer fabrication 360 process steps. The basic unit processes are photolithographic patterning, etching, doping, deposition of various materials, metallization, wafer cleaning, polishing, and furnace operations. Besides this unit process level, there are infrastructure unit operations such as clean room air conditioning, central exhaust abatement, water purification, or wastewater treatment. Subsequent manufacturing steps like dicing and packaging, utilization, and waste disposal of the final products were not included.

DRAM and logic wafer fabrication have a rather similar material demand and emission pattern per square meter of cleanroom installation, but a rather different productivity because DRAM products are less complex and have therefore a higher output of chips per time. Another key factor is the use of test wafers: logic devices require more test wafers, and although these are already recycled as much as possible, there remains a distinct impact to the process yield. Test wafers are used to control the process and are discarded after repeated use. Beyond the number of test wafers, the yield depends on the loss through breakage. In addition, due to layer errors not all dies present on the wafer are useful.

The available data relate to an average factory with 4,900 m^2 clean room space. For DRAM wafers a weekly capacity of 4,900 wafers and for logic wafers a capacity of 1,700 wafers was assumed.

For the processes investigated, inputs like chemicals, gases, water, electricity, natural gas, transportation, and infrastructure of the factory are included. The use of specific chemicals which are in proprietary use in some companies was excluded. The output process data are represented by air emissions, waste, and effluents to wastewater treatment. The reference period is the year 2005. The geographic reference area of the primary data is the world because it contains average data for approximately 80% of the world's semiconductor fabrication. But as secondary data of ecoinvent refers mainly on European data the overall geographic reference area was reduced to Europe. The functional unit is 1 m^2 fabricated DRAM or logic wafer, meaning 14 wafers of 300 mm diameter. A wafer is 0.75 mm thick and weighs approximately 150 g.

3.2 Life cycle inventory

The LCI is composed of primary and secondary data. The following primary data were available:

- Quantitative data on precursor chemicals, gases, water, and energy
- Quantitative data on direct emissions into the atmosphere

Table 6 Estimation of infrastructure service

Infrastructure		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
Semiconductor factory	Unit	1.37E−05	7.30E−06	2.27E−05

Table 7 Primary data for direct emissions to air

Direct emissions to air		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
2-Methylaminoethanol	kg	1.24E−02	6.61E−03	2.05E−02
Acetone	kg	8.37E−02	4.46E−02	1.39E−01
Al_2O_3	kg	1.46E−06	7.78E−07	2.42E−06
Ar	kg	2.72E+01	1.45E+01	4.51E+01
As	kg	2.24E−05	1.19E−05	3.71E−05
As_2O_3	kg	6.91E−08	3.68E−08	1.14E−07
AsH_3	kg	1.90E−05	1.01E−05	3.14E−05
B	kg	2.24E−05	1.19E−05	3.71E−05
B_2H_6	kg	1.95E−07	1.04E−07	3.22E−07
B_2O_3	kg	4.07E−07	2.17E−07	6.73E−07
Br_2	kg	4.72E−05	2.52E−05	7.82E−05
Butyl acetate	kg	6.71E−03	3.57E−03	1.11E−02
C_2F_6	kg	6.41E−03	3.42E−03	1.06E−02
$C_2H_5OC_2H_5$	kg	1.11E−03	5.94E−04	1.84E−03
C_4F_8	kg	5.26E−04	2.80E−04	8.71E−04
C_5F_8	kg	2.10E−03	1.12E−03	3.48E−03
CF_4	kg	1.58E−02	8.40E−03	2.61E−02
CH_2F_2	kg	3.10E−05	1.65E−05	5.13E−05
CH_3Br	kg	1.05E−04	5.57E−05	1.73E−04
CH_3Cl	kg	3.26E−04	1.74E−04	5.40E−04
CH_3F	kg	2.02E−05	1.08E−05	3.35E−05
CH_3OCH_3	kg	4.66E−05	2.48E−05	7.71E−05
CH_4	kg	1.26E+00	6.73E−01	2.09E+00
CHF_3	kg	4.17E−05	2.22E−05	6.90E−05
Cl_2	kg	1.23E−04	6.54E−05	2.03E−04
CO	kg	3.44E−03	1.83E−03	5.69E−03
CO_2	kg	1.89E+01	1.01E+01	3.12E+01
COF_2	kg	1.31E−04	6.96E−05	2.16E−04
Ethyl lactate	kg	2.64E−01	1.41E−01	4.37E−01
F_2	kg	6.14E−04	3.27E−04	1.02E−03
Gamma-butyrolactone	kg	2.68E−04	1.43E−04	4.44E−04
H_2	kg	2.53E−01	1.35E−01	4.19E−01
H_2O	kg	1.41E+04	7.49E+03	2.33E+04
H_2SO_4	kg	2.78E−02	1.48E−02	4.61E−02
HBr	kg	1.28E−04	6.84E−05	2.13E−04
HCl	kg	4.08E−03	2.17E−03	6.75E−03
He	kg	1.37E−01	7.28E−02	2.26E−01
Hexamethyldisilazane	kg	1.63E−05	8.67E−06	2.69E−05
HF	kg	5.95E−03	3.17E−03	9.86E−03
HNO_3	kg	3.14E−03	1.68E−03	5.21E−03
Isopropanol	kg	2.03E−01	1.08E−01	3.36E−01
Kr	kg	7.51E−04	4.00E−04	1.24E−03
Methyl nonafluorobutyl ether	kg	2.39E−03	1.27E−03	3.96E−03
N_2	kg	4.31E+05	2.30E+05	7.14E+05
N_2O	kg	1.62E−01	8.61E−02	2.68E−01
Ne	kg	3.52E−04	1.88E−04	5.83E−04
NF_3	kg	3.08E−04	1.64E−04	5.09E−04
NH_3	kg	3.31E−02	1.76E−02	5.48E−02

Table 7 (continued)

Direct emissions to air		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
NH_4Cl	kg	1.19E−05	6.33E−06	1.97E−05
N-Methyl-2-pyrrolidone	kg	1.89E−02	1.01E−02	3.13E−02
NO	kg	2.02E−05	1.07E−05	3.34E−05
NO_2	kg	1.18E−01	6.31E−02	1.96E−01
O_2	kg	1.21E+05	6.46E+04	2.01E+05
Organochlorine compounds	kg	7.49E−08	3.99E−08	1.24E−07
P	kg	2.33E−04	1.24E−04	3.86E−04
P_2O_5	kg	3.48E−05	1.85E−05	5.77E−05
PH_3	kg	9.41E−03	5.02E−03	1.56E−02
$PO(OC_2H_5)_3$	kg	5.05E−05	2.69E−05	8.36E−05
$PO(OCH_3)_3$	kg	1.31E−05	6.95E−06	2.16E−05
Propylene glycol	kg	1.63E−03	8.69E−04	2.70E−03
Propylene glycol methyl ether acetate (PGMEA)	kg	1.20E−02	6.42E−03	2.00E−02
SF_6	kg	1.72E−02	9.17E−03	2.85E−02
$Si(OC_2H_5)_4$	kg	1.73E−04	9.23E−05	2.87E−04
Si_2H_6	kg	1.36E−04	7.24E−05	2.25E−04
SiH_4	kg	5.52E−03	2.94E−03	9.13E−03
SiO_2	kg	2.12E−04	1.13E−04	3.51E−04
SO_2	kg	5.05E−04	2.69E−04	8.37E−04
Tetramethylammonium hydroxide	kg	4.38E−03	2.33E−03	7.26E−03
Trimethylsilanol	kg	1.80E−03	9.59E−04	2.98E−03
WF_6	kg	7.75E−06	4.13E−06	1.28E−05
WO_3	kg	1.52E−05	8.09E−06	2.51E−05

– Quantitative data and chemical composition of the effluent
– Quantitative data and chemical composition of the waste

Upstream processes for chemicals and gas production, transportation, infrastructure, and water and energy supply were supplemented by secondary or generic data. The upstream impacts of the wafer production processes up to the unprocessed wafer (like ingot production and wafer sawing) were also taken from an LCA database.

As the primary data available were time-related and not output-related, the reference flows based on the functional unit of 1 m^2 processed wafer were converted in accordance with the factors in Table 2. The number of test wafers and the loss through breakage and layer errors is based on expert judgment.

Table 3 shows the primary data for process chemicals, gases, and water for the life cycle inventory. The substances were assigned to the equivalent substances of ecoinvent. Where no equivalent ecoinvent substance was available, a similar chemical was assigned. Chemical mixtures like AsH_3 0.7% in H_2 were assessed as 0.7 kg AsH_3 and 99.3 kg H_2. For water-based solutions only the share of the dissolved substance was balanced. Although in semiconductor fabrication chemicals and gases of high purity are used, in the ecoinvent database only chemicals of average purity are available and had to be used.

Table 4 shows the demand for electric power and natural gas. Electric power is needed firstly for production processes and secondly for service processes such as production of cooling power, ultrapure water generation, climate control, etc. These service processes account for more than half of the overall electricity demand. Counted per fabricated 300 mm wafer, the overall demand amounts to 690 kWh per DRAM wafer and 2,140 kWh per logic wafer.

The ecoinvent dataset “natural gas, in industrial furnace” is applied for supply and use of natural gas. For electric power, the European UCTE electricity mix is assumed (“electricity, medium voltage, production UCTE, at grid”).

Since no primary data for transport for chemicals and waste were available, transport distances were estimated in line with the ecoinvent standard transport distances (Frischknecht et al. 2007) (Table 5).

The ecoinvent dataset “photovoltaic cell factory” was used for the infrastructure of the semiconductor factory and scaled, taking the higher demand for technical equipment and more stringent clean room conditions into account. The

Table 8 Composition of solid waste

Solid waste to residual material landfill		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
*AsO_3^{---}	kg	1.70E−07	9.04E−08	2.81E−07
*OCl^-	kg	1.65E−07	8.80E−08	2.73E−07
Al_2O_3	kg	1.14E+00	6.07E−01	1.89E+00
As	kg	9.62E−05	5.12E−05	1.59E−04
As_2O_3	kg	1.84E−03	9.81E−04	3.05E−03
B	kg	1.25E−04	6.66E−05	2.07E−04
B_2O_3	kg	2.70E−04	1.44E−04	4.47E−04
BO_3^{---}	kg	1.84E−06	9.78E−07	3.04E−06
Br^-	kg	6.20E−06	3.30E−06	1.03E−05
Br_2	kg	1.04E−07	5.54E−08	1.72E−07
C (undef.)	kg	2.54E−05	1.36E−05	4.21E−05
$Ca(OH)_2$	kg	8.80E−05	4.69E−05	1.46E−04
Ca^{++}	kg	5.12E−04	2.73E−04	8.48E−04
CaF_2	kg	4.50E+00	2.40E+00	7.45E+00
CH_3CH_2OH	kg	8.91E−07	4.75E−07	1.47E−06
Cl^-	kg	5.64E−03	3.00E−03	9.34E−03
Cl_2	kg	4.24E−08	2.26E−08	7.02E−08
CO_2	kg	5.55E−04	2.96E−04	9.20E−04
CO_3^{--}	kg	1.48E−02	7.86E−03	2.44E−02
Cu	kg	7.08E−03	3.77E−03	1.17E−02
Cu slurry	kg	1.62E+01	8.65E+00	2.69E+01
Cu^{++}	kg	1.30E+01	6.94E+00	2.16E+01
EDTA	kg	8.76E−08	4.67E−08	1.45E−07
Ethyl lactate	kg	8.06E+00	4.30E+00	1.34E+01
F^-	kg	6.25E−01	3.33E−01	1.03E+00
Fe^{++}	kg	3.45E−06	1.84E−06	5.71E−06
Gamma-butyrolactone	kg	6.40E−02	3.41E−02	1.06E−01
H_2O	kg	5.37E+01	2.86E+01	8.89E+01
H_2SO_4	kg	2.55E+01	1.36E+01	4.22E+01
H_3PO_4	kg	1.94E−07	1.04E−07	3.22E−07
HCl	kg	2.21E−08	1.18E−08	3.65E−08
HF	kg	9.87E+00	5.26E+00	1.63E+01
Hexafluoro-acetylacetonate	kg	4.15E−02	2.21E−02	6.88E−02
Hexamethyldisilazane	kg	1.03E−01	5.49E−02	1.71E−01
HNO_3	kg	1.55E−02	8.26E−03	2.57E−02
K^+	kg	1.04E−02	5.52E−03	1.72E−02
Methanol	kg	4.17E−08	2.22E−08	6.90E−08
Mg^{++}	kg	6.90E−04	3.68E−04	1.14E−03
Na^+	kg	7.39E−04	3.94E−04	1.22E−03
NH_3	kg	1.06E−07	5.65E−08	1.76E−07
NH_4^+	kg	5.91E−01	3.15E−01	9.79E−01
NH_4Cl	kg	2.51E−02	1.34E−02	4.15E−02
NH_4OH	kg	5.74E−10	3.06E−10	9.50E−10
N-Methyl-2-pyrrolidone	kg	2.14E−01	1.14E−01	3.54E−01
NO_2^-	kg	3.32E−10	1.77E−10	5.49E−10
NO_3^-	kg	2.94E−05	1.56E−05	4.86E−05
P	kg	3.67E−03	1.96E−03	6.08E−03
P_2O_5	kg	1.41E−02	7.49E−03	2.33E−02

Table 8 (continued)

Solid waste to residual material landfill		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
Propylene glycol methyl ether acetate (PGMEA)	kg	1.45E+00	7.71E−01	2.40E+00
PO_4^{---}	kg	9.23E−05	4.92E−05	1.53E−04
Organochlorine compounds	kg	2.92E−07	1.56E−07	4.84E−07
Si	kg	4.48E−03	2.39E−03	7.42E−03
Si_3N_4	kg	2.16E−02	1.15E−02	3.58E−02
SiO_2	kg	1.28E+00	6.82E−01	2.12E+00
SO_3^{--}	kg	4.16E−05	2.22E−05	6.90E−05
SO_4^{--}	kg	1.97E+01	1.05E+01	3.26E+01
Tetramethylammonium hydroxide	kg	1.70E−06	9.06E−07	2.82E−06
W	kg	1.38E−01	7.36E−02	2.29E−01
WO_3	kg	1.57E−01	8.39E−02	2.61E−01
Ion exchange resin	kg	6.71E−01	3.58E−01	1.11E+00

baseline was the value of 4E–07 units per square meter of manufactured silicon solar cell. This value is multiplied by three to represent the higher burden for the clean room conditions, based on the experience of M+W Germany in planning such factories. In order to involve the larger effort for technical equipment, this is multiplied again using the ratio of the annual throughput for the solar cell factory of 100,000 m^2/a to the annual throughput of the semiconductor factory of 5,290 m^2/a for logic wafer or 16,400 m^2/a for DRAM wafer. Table 6 shows the resulting values.

Data for direct emissions to the atmosphere were partly calculated indirectly via the input chemicals and partly measured at existing facilities (Table 7).

The chemical composition of the solid waste generated during average wafer processing is shown in Table 8. Data are modeled according to input chemicals. Deposition on a residual material landfill was assumed. A separate dataset was created, based on the Excel tool developed in the framework of the waste section in ecoinvent (Doka 2009). Table 9 shows the content of the solvent waste. For solvent waste the ecoinvent dataset "disposal, solvent mixture, 16.5% water, to hazardous waste incineration" was used.

A separate dataset was also created for wastewater treatment, based on the Excel tool developed in the framework of the waste section in ecoinvent (Doka 2009). The chemical composition of the wastewater is shown in Table 10.

3.3 Results of life cycle impact assessment

The impact assessment results show that environmental damage for 1 m^2 fabricated DRAM and logic wafer is dominated by energy consumption in almost all categories, followed by the upstream production of chemicals (Figs. 1 and 2). In the chemicals sector, the utilization of nitrogen makes the largest contribution. As regards ecosystem quality, the wastewater treatment is highly significant. The share of transport, waste management, and infrastructure services is low in all categories.

Including all the inputs, a total of 6.9 t of CO_2 equivalents is emitted per square meter of processed DRAM wafer, while for a logic wafer 21 t of CO_2

Table 9 Composition of solvent waste

Solvent waste to hazardous waste incineration		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
2-Methylaminoethanol	kg	2.96E+00	1.58E+00	4.90E+00
Butyl acetate	kg	1.60E+00	8.53E−01	2.65E+00
$CH_3CH(OH)CH_3$	kg	1.83E+01	9.73E+00	3.02E+01
CH_3COCH_3	kg	7.11E−01	3.79E−01	1.18E+00
Methyl nonafluorobutyl ether	kg	5.71E−01	3.04E−01	9.45E−01
N-Methyl-2-pyrrolidone	kg	2.59E+00	1.38E+00	4.28E+00
Propylene glycol	kg	3.89E−01	2.07E−01	6.44E−01
Tetramethylammonium hydroxide	kg	3.24E−02	1.72E−02	5.36E−02

equivalents per square meter are emitted. The direct emissions of greenhouse gases cause about 6% of the total effect in the climate change category. The direct greenhouse gas emissions include NF_3, PFCs and HFCs, carbon dioxide, and methane, with the carbon dioxide coming from the oxidation of VOCs, PFCs, and HFCs. The energy consumption is responsible for approximately 75% of greenhouse gas emissions.

3.4 Comparison with ecoinvent data

Some differences were apparent between the results of this study and the ecoinvent dataset "wafer, fabricated, for integrated circuit, at plant", which refers to the production of DRAM wafers. Figure 3 shows the results of the impact assessment for this study compared with the ecoinvent dataset. On the one hand substantial differences between

Table 10 Composition of wastewater

Wastewater to wastewater treatment plant class 3		Per hour	Per square meter output DRAM wafer	Per square meter output logic wafer
*OCl^-	kg	3.86E+00	2.06E+00	6.39E+00
*AsO_3—	kg	8.24E−04	4.39E−04	1.36E−03
Acetone	kg	4.18E−02	2.23E−02	6.93E−02
BO_3—	kg	8.91E−03	4.75E−03	1.48E−02
Br^-	kg	3.06E−02	1.63E−02	5.07E−02
C (undef)	kg	8.52E−02	4.54E−02	1.41E−01
Ca^{++}	kg	3.48E+00	1.85E+00	5.76E+00
Ethanol	kg	4.32E−03	2.30E−03	7.16E−03
Cl^-	kg	2.81E+01	1.50E+01	4.65E+01
CO_3^{--}	kg	7.53E+01	4.01E+01	1.25E+02
Cu^{++}	kg	7.55E−01	4.02E−01	1.25E+00
EDTA	kg	1.72E+00	9.14E−01	2.84E+00
F^-	kg	2.36E−01	1.26E−01	3.91E−01
Fe^{++}	kg	3.73E−01	1.99E−01	6.18E−01
H_2O	kg	8.26E+04	4.40E+04	1.37E+05
Isopropanol	kg	9.30E−02	4.95E−02	1.54E−01
K^+	kg	5.06E+01	2.70E+01	8.39E+01
Methanol	kg	2.02E−04	1.08E−04	3.35E−04
Mg^{++}	kg	3.86E+00	2.06E+00	6.39E+00
Na^+	kg	4.09E+00	2.18E+00	6.77E+00
NH_4^+	kg	3.16E+00	1.68E+00	5.23E+00
NO_2^-	kg	1.61E−06	8.58E−07	2.67E−06
NO_3^-	kg	3.86E+00	2.06E+00	6.39E+00
PO_4^{---}	kg	3.85E+00	2.05E+00	6.38E+00
Organochlorine compounds	kg	7.49E−09	3.99E−09	1.24E−08
SO_3^{--}	kg	2.02E−01	1.08E−01	3.35E−01
SO_4^{--}	kg	3.79E+01	2.02E+01	6.27E+01
Tetramethylammonium hydroxide	kg	1.38E+01	7.38E+00	2.29E+01
Al_2O_3	kg	1.14E+00	6.07E−01	1.89E+00
As_2O_3	kg	1.42E−05	7.55E−06	2.35E−05
Cu	kg	1.71E−02	9.11E−03	2.83E−02
Slurry	kg	8.54E−01	4.55E−01	1.41E+00
Thereof H_2O	kg	7.7E−01	4.09E−01	1.27E+00
Thereof NaOH	kg	3.0E−04	1.64E−04	5.09E−04
Thereof SiO_2	kg	8.5E−02	4.55E−02	1.41E−01
SiO_2	kg	1.15E+00	6.12E−01	1.90E+00
W	kg	2.44E−02	1.30E−02	4.03E−02
WO_3	kg	3.67E−03	1.96E−03	6.08E−03

the production of DRAM and logic wafers are evident. This is not taken into account in ecoinvent, as the same wafer dataset is used for both types of chip.

One reason for the higher values of ecoinvent data by comparison with DRAM wafer production according to M +W Germany data is the assumption for the yield. ecoinvent takes a value of 55%, which represents the average of several widely ranged literature values. This value is unrealistic in current practice and as an average, since at such a low yield the process cannot be operated economically.

The low yield is not solely responsible for the differences. Figure 4 shows the results broken down by their contributions. Waste treatment and energy consumption show the biggest differences, at least for DRAM fabrication.

In the case of waste treatment, the amount of waste is crucial for the difference. In the ecoinvent data, waste is assumed to be 7.8 kg/cm^2, while according to M+W Germany only 9.8 g/cm^2 for DRAM wafer and 31 g/cm^2 for the logic wafer can be presumed. The elemental composition was available for most of the waste data from M+W Germany, so that waste treatment could be assessed specifically with the ecoinvent Excel tool. The results of the impact assessment per kilogram of the dataset determined in this way and the ecoinvent dataset on waste treatment differ only slightly.

Other differences exist in the data on energy consumption for the wafer processing. The energy consumption for both datasets is composed of electricity and natural gas, the quantity is shown in Table 11. Natural gas consumption especially is 30 to 80 times higher for ecoinvent compared to this study. As ecoinvent assumes the same energy demand for memory and logic wafer fabrication, the quantity for logic wafer seems to be accurate. However, the underlying literature source for ecoinvent refers only to DRAM fabrication, for which the quantity of nearly 100,000 MJ is almost three times higher than M+W Germany data.

A reason for the high-energy consumption in ecoinvent seems to be a lack of data, since only two literary sources were cited. As technology is developing rapidly in semiconductor fabrication, swift improvements in energy efficiency in this field can be expected too, so that the data quickly become outdated.

The differences in the damage category of human health in the case of wastewater treatment are due to the assumptions regarding the heavy metal content of the wastewater. Since no data on heavy metals were available in the underlying literature sources of the ecoinvent dataset, only assumptions were made here. These, however, are not in line with the actual average heavy metal content. In the effluent of a semiconductor factory neither cadmium nor chromium or lead can be found. By contrast with human health, the impact category of ecosystem quality is underestimated in ecoinvent data. The composition of organic and saline wastewater components is available in more detail in M+W Germany data and leads to more adverse effects for ecosystem quality.

Electronics data from ecoinvent data v2.0 have been applied in several recent publications (Dettling and Margni

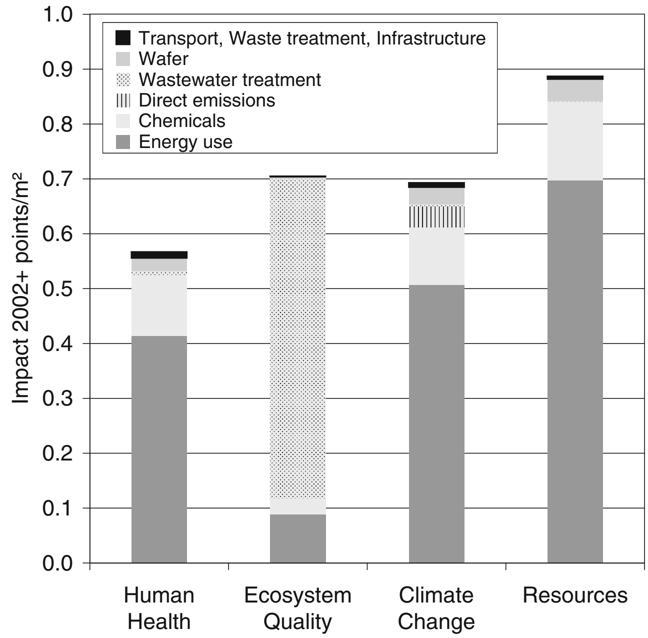

Fig. 1 Impact assessment result for 1 m^2 processed DRAM wafer including upstream processes (cradle to gate)

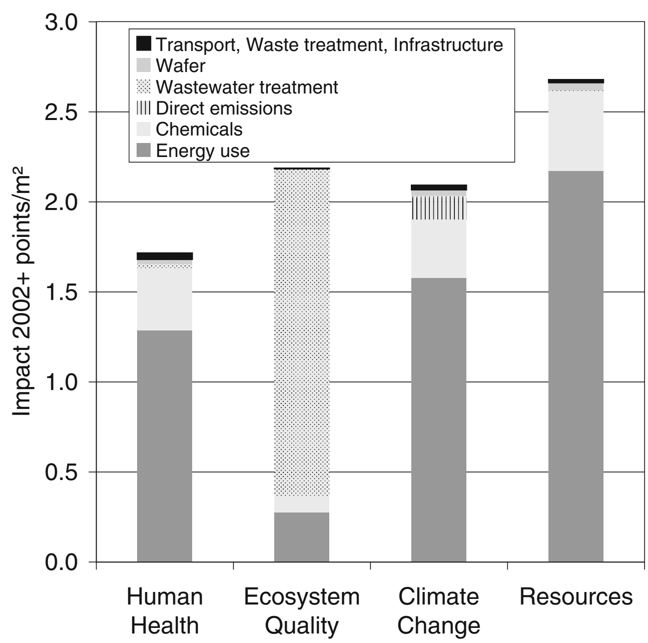

Fig. 2 Impact assessment result for 1 m^2 processed logic wafer including upstream processes (cradle to gate)

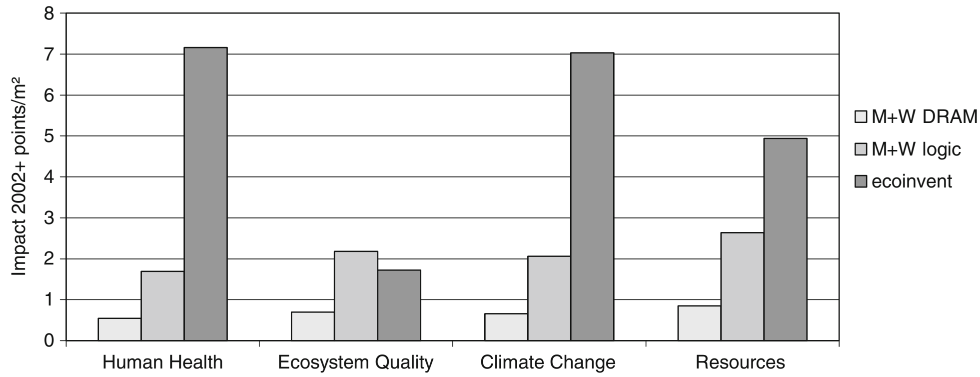

Fig. 3 Comparison of impact assessment results of M+W Germany data and ecoinvent data per square meter of processed wafer

2009; Duan et al. 2009; Eugster et al. 2007; Moberg et al. 2008). Companies like Hewlett-Packard are using ecoinvent data too (Ord et al. 2009) and it can be assumed that other electronics companies are also using these data for internal purposes. Dettling and Margni (2009) investigated electric hand drying systems. For the impact category climate change they found a contribution of 212 kg CO_2eq for materials production, including 173 kg CO_2eq for electronic components. With the data of this study, the contribution of materials production would decrease to 168 kg CO_2eq or by 21%. The individual effect of the electronic component is reduced by one fourth.

4 Solar cell fabrication

4.1 Scope

The system under study was the fabrication of solar cells produced on a carrier of thin elemental silicon wafer. This can be monocrystalline (older technology) or polycrystalline (newer technology). Production technology to manufacture monocrystalline cells differs from that for polycrystalline silicon solar cells in only one step, the texturing. The other steps (doping, anti-reflective coating, and metallization) can vary depending on the different equipment providers. There are different technologies for waste, wastewater, and exhaust processing, but these are more dependent on the size and possibly the country of the installation than on the underlying production technologies.

Not all the potential variants among the very large number of theoretically possible combinations of technology and production capacity were investigated, but a number of scenarios that played a significant role in the planning and construction practices in the years 2006 to 2008 were explored. A so far only hypothetical factory with 1 GW annual production of solar cells has also been calculated to extrapolate today's technology. With four basic scenarios (1 to 4), three variants were considered, which however all derive from scenario 3 (3a–c). To a limited extent this compilation also allows comparisons between individual technologies. An overview of the scenarios is given in Table 12.

This is a cradle-to-gate investigation, consisting of primary gate-to-gate data for the process of solar cell fabrication from factory planning. The upstream processes of solar cell production are supplemented with

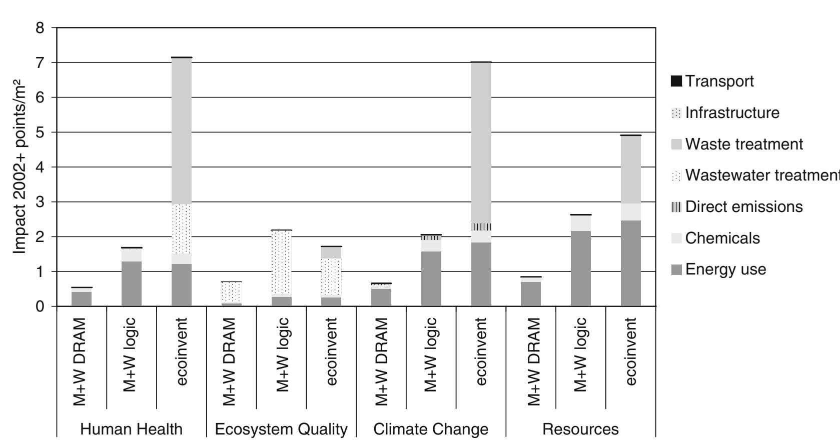

Fig. 4 Comparison of impact assessment results of M+W Germany data and ecoinvent data according to contribution

Table 11 Comparison of energy consumption for processing 1 m^2 wafer

Per square meter output	ecoinvent	M+W Germany	
		DRAM	Logic
Electric energy	99,360 MJ	35,000 MJ	110,000 MJ
Natural gas	58,359 MJ	700 MJ	2,000 MJ

generic data. Chemicals, gases, water, electricity, natural gas, transportation, and infrastructure of the factory are included for the investigated input process data. The output process data are represented by air emissions, waste, and wastewater treatment. Subsequent manufacturing steps up like panel production, utilization, and waste disposal of the final products are not included. Input material for all investigated variants was monocrystalline or polycrystalline wafer, respectively, size 156×156 mm^2 and 200 μm thick, assuming a 6% loss of wafers during production (Jungbluth and Tuchschmid 2007). The functional unit refers to 1 m^2 fabricated solar cells, equivalent to 41 single wafers. Mounted in a solar panel of 1 m^2, this would result in a capacity of 0.14 kW_p for monocrystalline and 0.13 kW_p for polycrystalline solar cells (Jungbluth and Tuchschmid 2007). The reference period covers the year 2007 and geographic reference area is Europe.

4.2 Life cycle inventory

The LCI is composed of primary and secondary data. The primary data comprise:

- Quantitative data on chemicals, gases, water, and energy
- Quantitative data on direct emissions into the atmosphere
- Quantitative data of the effluent
- Quantitative data of the waste

Table 13 shows primary data for scenarios 1 to 4.

Table 12 Overview of the scenarios investigated for solar cell production

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Capacity	60 MW/a	60 MW/a	240 MW/a	1,000 MW/a extrapol
Material	Monocrystalline	Polycrystalline	Polycrystalline	Polycrystalline
Process steps				
Texturing	Alkaline, no central scrubbing and external disposal of liquid waste	Acid texture, HF + NO_x scrubbing and external disposal of liquid waste	Acid texture, HF + NO_x scrubbing and external disposal of liquid waste	Acid texture, HF + NO_x scrubbing and onsite treatment of liquid waste
Doping	$POCl_3$, central scrubbing	$POCl_3$, central scrubbing	H_3PO_4, central scrubbing	EtOH + H_3PO_4, central scrubbing
PSG etching	Wet, central scrubbing	Wet, central scrubbing	Wet, central scrubbing	Wet, central scrubbing
Si_3N_4 deposition	Batch tool, local abatement	Batch tool, local abatement	Inline tool, local abatement	Inline tool, local abatement
Printer/dryer	3 dryers, condensation (1-stage)	3 dryers, condensation (1-stage)	3 dryers, condensation (1-stage)	2 dryers, condensation (1-stage)
Firing	No treatment	No treatment	No treatment	No treatment
Edge isolation	Laser	Laser	Laser	Laser
Facilities installed				
Wastewater	Neutralization, HF	Treatment	Neutralization, HF treatment	Neutralization, HF treatment
Acid exhaust	Central acid scrubbing	NO_x+HF and central acid scrubbing	NO_x+HF and central acid scrubbing	NO_x+HF and central acid scrubbing
VOC exhaust	–	–	VOC treatment (regenerative/recuperative burner)	VOC treatment (RTO)
Production environment	Clean room class 10,000	Clean room class 10,000	Clean room class 100,000	Clean room class not specified
	Scenario 3a	Scenario 3b	Scenario 3c	
	As 3, but with solvent in doper and RTO as VOC treatment	As 3, but with $POCl_3$ instead of H_3PO_4	As 3, but only 2 dryer stages, firing with condensation	

PSG phosphorus silicate glass, *RTO* regenerative thermal oxidation

Table 13 Primary data for scenario 1 to 4

Input		Scenario 1	Scenario 2	Scenario 3	Scenario 4
		Per square meter output			
Chemicals and gases					
2,2,4-Trimethyl-1,3-pentadiol-monoisobutyrate	kg	8.80E−03	8.80E−03	8.80E−03	1.05E−02
1-Propoxy-2-propanol/PGPE	kg	3.52E−03	3.52E−03	3.52E−03	4.22E−03
Diethylene glycol monobutyl ether	kg	1.76E−03	1.76E−03	1.76E−03	2.11E−03
1-Butoxy-2-propanol/PGBE	kg	3.52E−03	3.52E−03	3.52E−03	4.22E−03
Ethanol	kg	–	–	–	4.64E−02
Isopropanol	kg	1.77E−01	–	–	–
$Ca(OH)_2$	kg	1.51E−02	5.10E−01	5.34E−02	7.23E−01
H_2O_2	kg	–	4.53E−04	4.53E−04	5.43E−04
H_2SO_4	kg	8.76E−02	1.01E−01	1.01E−01	7.44E−01
H_3PO_4	kg	–	–	1.35E−02	1.62E−02
HCl	kg	6.30E−04	2.56E−04	2.56E−04	3.07E−04
HF (50%)	kg	6.47E−02	5.05E−01	5.05E−01	6.06E−01
HNO_3	kg	–	1.73E−01	1.73E−01	2.07E−01
N_2	kg	1.15E+00	1.14E+00	1.14E+00	1.37E+00
NaOH (40%)	kg	5.86E−01	8.64E−01	2.12E−01	6.76E−01
NH_3	kg	2.19E−02	2.19E−02	2.19E−02	2.62E−02
$POCl_3$	kg	1.33E−02	1.33E−02	–	–
R134a	kg	3.12E−05	3.21E−05	2.73E−05	2.44E−05
SiH_4	kg	2.91E−03	2.91E−03	3.55E−03	4.26E−03
City water	kg	1.71E+02	1.21E+02	8.64E+01	9.18E+01
Energy					
Electric power (clean room)	kW	2.73E+01	2.78E+01	1.93E+01	2.08E+01
Electric power (others)	kW	9.20E+00	7.97E+00	6.22E+00	6.27E+00
Natural gas	kg	6.07E−02	6.07E−02	2.47E−01	1.38E−01
Output					
Direct emissions to air					
Terpineol	kg	1.26E−02	1.26E−02	3.53E−04	4.24E−04
2,2,4-Trimethyl-1,3-pentadiol-monoisobutyrate	kg	6.53E−03	6.31E−03	1.77E−04	2.12E−04
1-Propoxy-2-propanol/PGPE	kg	2.61E−03	2.52E−03	7.07E−05	8.48E−05
Diethylene glycol monobutyl ether	kg	1.31E−03	1.26E−03	3.53E−05	4.24E−05
1-Butoxy-2-propanol/PGBE	kg	2.61E−03	2.52E−03	7.07E−05	8.48E−05
Ethanol		–	–	–	2.67E−02
Isopropanol	kg	1.47E−02	–	–	–
Cl_2	kg	4.61E−05	4.61E−05	–	–
CO_2	kg	1.67E−01	1.67E−01	6.84E−01	3.84E−01
H_2	kg	1.10E−02	3.64E−04	4.44E−04	5.32E−04
HF	kg	1.38E−04	6.89E−04	6.89E−04	8.26E−04
HNO_3	kg	–	1.19E−04	1.19E−04	1.43E−04
N_2	kg	1.99E+03	1.99E+03	1.16E+03	1.38E+03
NH_3	kg	3.73E−05	5.23E−04	5.20E−04	6.24E−04
NO	Kg	–	3.64E−03	3.64E−03	4.36E−03
NO_2	kg	–	8.92E−03	1.24E−02	1.66E−02
O_2	kg	5.23E+02	5.21E+02	3.02E+02	3.62E+02
$POCl_3$	kg	6.32E−04	6.32E−04	–	–
R134a	kg	3.12E−05	3.21E−05	2.73E−05	2.44E−05
Si	kg	3.17E−08	3.17E−08	3.17E−08	3.80E−08

Table 13 (continued)

Input		Scenario 1 Per square meter output	Scenario 2	Scenario 3	Scenario 4
Chemicals and gases					
Si_3N_4	kg	3.33E−04	1.47E−04	1.47E−04	1.77E−04
SiO_2	kg	2.63E−03	4.91E−06	5.98E−06	7.17E−06
H_2O	kg	1.16E+01	1.22E+01	5.95E+00	5.34E+00
Waste					
disposal, waste, Si waferprod., inorg, 9.4% water, to residual material landfill	kg	2.33E+00	2.98E+00	2.82E+00	2.53E+00
Disposal, solvent mixture, 16.5% water, in hazardous waste incineration	kg	1.72E−01	9.94E−03	1.08E−02	3.16E−02
Wastewater					
Treatment, wafer fabrication effluent, to wastewater treatment, class 2	m^3	1.59E−01	1.07E−01	7.91E−02	8.70E−02

For supply and use of natural gas the ecoinvent dataset "natural gas, in industrial furnace" is applied. Electric power is needed, especially to create clean room conditions, for which the European UCTE electricity mix is assumed ("electricity, medium voltage, production UCTE, at grid").

The appropriate datasets from ecoinvent were used for the waste and wastewater treatment.

Where no primary process data were available, data from Jungbluth and Tuchschmid (2007) were applied. A lack of primary data occurred for metallization pastes. According to Jungbluth and Tuchschmid (2007), three different metallization pastes are used. For the process investigated a total consumption of 1.5 g/wafer was known. The consumption of the three types of metallization pastes was calculated for this value with the ratio of the metallization pastes according to Jungbluth and Tuchschmid (2007). Since the composition of the metallization pastes was unknown, the same data as in Jungbluth and Tuchschmid (2007) were used. No primary data were available for emissions from metallization pastes. In Jungbluth and Tuchschmid (2007) air emissions of 0.773 g/m^2 each were adopted for aluminum, lead, silver, and tin. This, however, seemed too high, as it would mean an hourly emission of 42.5 g. Thus, the values were reduced by a factor of 1/100 (Table 14).

Since no primary data for transport for chemicals and waste were available, transport distances were estimated in line with the ecoinvent standard transport distances (Frischknecht et al. 2007) (Table 15).

For the infrastructure of the factory, the ecoinvent dataset "photovoltaic cell factory" was used (see Table 15).

As the primary data available were time-related, the reference flows based on the functional unit of 1 m^2 wafers manufactured were converted in accordance with the factors in Table 16.

4.3 Results of life cycle impact assessment

The results show that the upstream process of silicon wafer production causes higher potential environmental impact than the solar cell fabrication itself. Depending on the category, the share varies between 15% and 33%. Within the process of solar cell fabrication all impact categories are dominated by energy consumption. Fur-

Table 14 Secondary data for metallization paste and its emissions for scenario 1–4

Metallization paste		Per square meter output
Metallization paste, front side	kg	5.76E−03
Metallization paste, back side	kg	3.84E−03
Metallization paste, back side Al	kg	5.60E−02
Emissions from metallization paste		
Aluminum	kg	7.72E−06
Lead	kg	7.72E−06
Silver	kg	7.72E−06
Tin	kg	7.72E−06

Table 15 Secondary data for transport and infrastructure for scenario 1–4

Transport		Per square meter output
Transport, transoceanic freight ship	tkm	3.06E−02
Transport, lorry >16 t, fleet average	tkm	2.74E−01
Transport, freight, rail	tkm	1.52E+00
Infrastructure		
Photovoltaic cell factory	Unit	4.00E−07

Table 16 Factors for conversion of time-related material and energy flows to the reference flows

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	
Capacity (input)	2,400	2,400	9,600	40,000	wf/h
Edge length wafer	0.156	0.156	0.156	0.156	m
Area wafer	0.0243	0.0243	0.0243	0.0243	m^2/wf
Number of wafer per m^2	41.1	41.1	41.1	41.1	wf/m^2
Throughput in m^2 (input)	58.4	58.4	233.6	973.3	m^2/h
Loss	6	6	6	6	%
Throughput in m^2 (output)	55.0	55.0	220.0	916.7	m^2/h

thermore, the upstream production of chemicals, particularly in the damage category human health, accounts for a significant proportion. Also direct process emissions are more relevant in this category than in others. The effluents of wastewater treatment contribute mainly to the category ecosystem quality. The share of transport, waste treatment, and infrastructure services is low in all categories.

Looking only at the greenhouse gas emissions, in silicon wafer manufacturing approximately 130 kg of CO_2 equivalents per square meter are emitted, while the solar cell fabrication process emits only 20 kg of CO_2 equivalents per square meter.

The following figures consider only the process of solar cell fabrication without the prechain for wafer production. Scenario 1 is shown separately and scenarios 2 to 4 are compared directly. Only scenario 1 deals with monocrystalline solar cell fabrication, which cannot be compared directly with the polycrystalline solar cells due to the higher current efficiency in the use phase (Fig. 5).

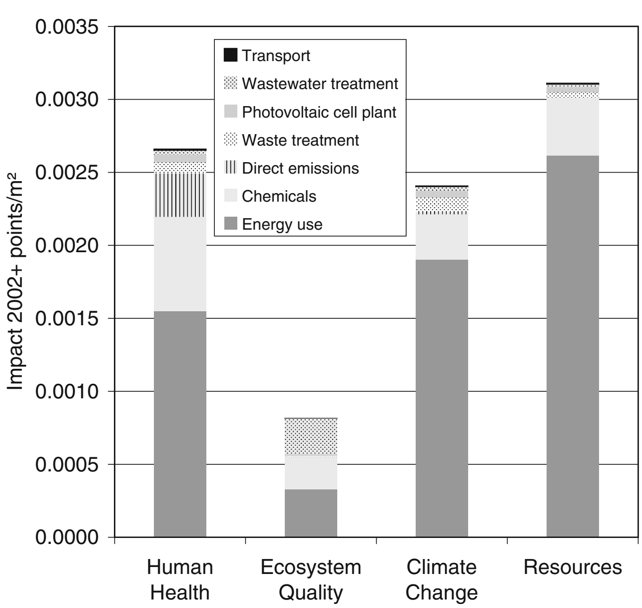

Fig. 5 Impact assessment result for scenario 1 for the fabrication process of 1 m^2 monocrystalline silicon solar cell

The results of scenarios 2 to 4, which are all related to the fabrication of polycrystalline solar cells, are compared below. The results produced by Scenario 3c are nearly identical to those for Scenario 3, which is why these are not shown separately. Scenarios 3, 3a, and 3b, which all represent production in a factory with a capacity of 240 MW/a, show significantly reduced environmental impacts by comparison with Scenario 2. This is due to lower energy consumption. Between them, they differ only minimally, as Fig. 6 shows. This means that different technologies only play a minor role for the overall environmental impact. Scenario 4 shows no economies of scale by increasing capacity to 1,000 MW.

4.4 Comparison with ecoinvent data

Ecoinvent data for silicon solar cell manufacturing are mainly based on de Wild-Scholten (2007), which seems to be a reliable data basis since ecoinvent results and the results of this study are very similar. The assumption made by ecoinvent to use the same data for monocrystalline and polycrystalline solar cell fabrication is backed up by the results of this study (Fig. 7).

5 Conclusions

The upstream process for production of silicon wafers is much more relevant for solar cell fabrication than for semiconductor fabrication, since the latter process is much more complex and therefore more resource-intensive. An improvement in wafer production would have greater influence on the environmental impact for solar cells than on that for microchips.

In both fabrication processes energy consumption, specifically consumption of electricity, is responsible for most of the potential environmental impacts. For solar cell fabrication, the supporting functions are more energy consuming than the production process itself. Still, in semiconductor fabrication more than half of the electric

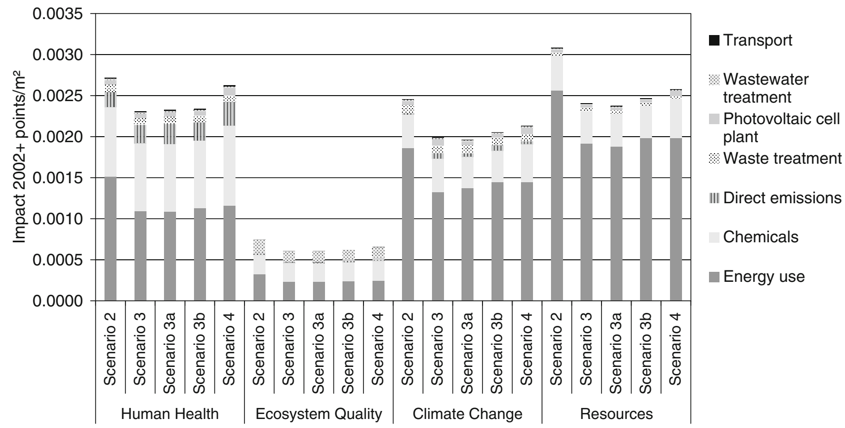

Fig. 6 Comparison of impact assessment results of scenarios 2, 3, 3a, 3b, and 4 for the fabrication process of 1 m^2 polycrystalline silicon solar cells

power is needed for secondary processes. This indicates that the production processes have a high demand for cooling, heating, ultrapure water, and other support functions, which have so far not been fully optimized. Many possibilities of saving energy in both production and support functions are being discussed today. These include reduced runtime for vacuum pumps ("smart idle"), high temperature cooling loops which remove waste heat at a higher temperature level than today, reuse of ultrapure water, and many others. Similar optimization is to be expected with solar cell production too, as the relatively fast ramp up during recent years has led to suboptimal infrastructure in terms of both energy and material efficiency. As electricity consumption is relevant for the overall result, it is worth looking at the electricity mix. More and more solar cells are being fabricated in China, where the electricity supply is based on coal with higher environmental impact than the electricity supply in Europe. As energy payback time is a relevant parameter for solar cells, more resource efficiency in solar cell fabrication would contribute mainly to reducing this payback time. Consumption of chemicals is also relevant for the overall environmental impact. This impact might be underestimated, as chemicals and gases of high purity are used, but the assessment only refers to average purity. In semiconductor fabrication the use of nitrogen can be improved, as consumption is very high.

A comparison with the present ecoinvent dataset "wafer, fabricated, for integrated circuit, at plant" shows large differences, indicating the rapid development in this area. ecoinvent data are mixed from different literature sources, whereas the analysis presented here is based on data from a single source and is therefore more consistent and reliable. Data will be provided to the ecoinvent Centre for an update of the dataset. As the dataset "wafer, fabricated, for integrated circuit, at plant" is used directly or indirectly in more than 60 other ecoinvent datasets, it is presumed that replacement will have a significant impact on some other datasets in this area. In the case of silicon solar cells, the results of this study and the ecoinvent data are very similar and the impact of different fabrication processes appears to be minor.

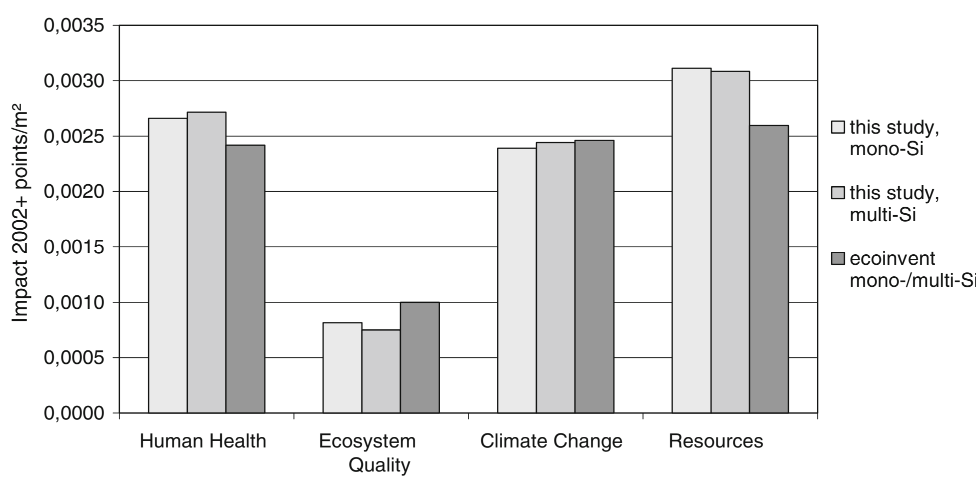

Fig. 7 Impact assessment results of this study (Scn. 1+2) compared with ecoinvent data for 1 m^2 fabricated solar cell without upstream process of wafer production

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References

Boyd S, Horvath A, Dornfeld D (2009) Life-cycle energy and global warming emissions of semiconductor logic. Environ Sci Technol 43(19):7303–7309

Boyd S, Horvath A, Dornfeld D (2010) Life-cycle assessment of computational logic produced from 1995 through 2010. Environ Res Let 5:014011

de Wild-Scholten M (2007) Environmental life cycle inventory of crystalline silicon photovoltaic system production-status 2005/2006. Energy Research Centre of the Netherlands, Petten

Dettling J, Margni M (2009) Comparative environmental life cycle assessment of hand drying systems: the XLERATOR hand dryer. Conventional hand dryers and paper towel systems. Quantis, Salem

Doka G (2009) Life cycle inventories of waste treatment services. Final report ecoinvent v2.0. No. 13. Swiss Centre for Life Cycle Inventories, St. Gallen

Duan H, Eugster M, Hischier R, Streicher-Porte M, Li J (2009) Life cycle assessment study of a Chinese desktop personal computer. Sci Total Environ 407(5):1755–1764

ecoinvent Centre (2007) ecoinvent data v2.0. ecoinvent reports No. 1–25. In: Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland

Eugster M, Hischier R, Duan H (2007) Key environmental impacts of the Chinese EEE-industry—a life cycle assessment study. Empa, St.Gallen

Frischknecht R, Althaus H-J, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Jungbluth N, Nemecek T, Rebitzer G, Spielmann M (2007) Overview and methodology. Final report ecoinvent v2.0 No.1. Swiss Centre for Life Cycle Inventories, Duebendorf

Hilleringmann U (2004) Silizium-Halbleitertechnologie. Teubner, Wiesbaden

Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 8 (6):324–330

Jungbluth N, Tuchschmid M (2007) Photovoltaics. Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Final report ecoinvent v2.0. No. 6. Swiss Centre for Life Cycle Inventories, Duebendorf

Jungbluth N, Bauer C, Dones R, Frischknecht R (2005) Life cycle assessment for emerging technologies: case studies for photovoltaic and wind power. Int J Life Cycle Assess 10(1):24–34

Krishnan N, Boyd S, Somani A, Raoux S, Clark D, Dornfeld D (2008) A hybrid life cycle inventory of nano-scale semiconductor manufacturing. Environ Sci Technol 42(8):3069–3075

Liu CH, Lin SJ, Lewis C (2010) Life cycle assessment of DRAM in Taiwan's semiconductor industry. J Cleaner Prod 18(5):419–425

Moberg A, Borggren C, Finnveden G, Tyskeng S (2008) Effects of a total change from paper invoicing to electronic invoicing in Sweden. A screening life cycle assessment focusing on greenhouse gas emissions and cumulative energy demand. KTH Centre for Sustainable Communications, Stockholm

Murphy CF, Kenig GA, Allen DT, Laurent J-P, Dyer DE (2003) Development of parametric material, energy, and emission inventories for wafer fabrication in the semiconductor industry. Environ Sci Technol 37(23):5373–5382

Ord J, Canonico S, Strecker T, Chappell E (2009) Product Environmental Metrics for Printers. GreenMetrics '09. 15 June 2009. Seattle, WA, USA

Stoppato A (2008) Life cycle assessment of photovoltaic electricity generation. Energy 33(2):224–232

Williams ED, Ayres RU, Heller M (2002) The 1.7 kilogram microchip: energy and material use in the production of semiconductor devices. Environ Sci Technol 36(24):5504–5510